Fermi National Accelerator Laboratory

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Ramping of Solid Iron Analysis Magnets In Experimental Areas

BM109 Preliminary Results

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RAMPING OF SOLID IRON ANALYSIS MAGNETS IN EXPERIMENTAL AREAS

BM109 PRELIMINARY RESULTS

1. INTRODUCTION

The long main ring TeV pulse period of 60 sec with a 20 sec flattop makes it attractive to ramp solid iron magnets, such as BM109's, etc., in synchronism with the main ring pulse. Annual energy cost savings for a BM109 could be up to a maximum of $6.6 per hour or $58,000 per year. Are there 10 or more magnets we could ramp? What is the lag between the magnet excitation current and the magnet field? It is probably small because these magnets have large air gaps and therefore relatively short (order of one second) time constants. Some preliminary measurements showing the lag between the excitation current and the magnet field for a BM109 are included. Ramping BM109's seems practical if they are programmed up 5 seconds ahead of the main ring pulse. Maybe ramping BM109's should be tried at a few locations to gain some experience. Any comments from readers will be appreciated.

2. COMPARISON OF RAMPING VERSUS DC OPERATION

2.1 ADVANTAGES

2.1.1 SUBSTANTIAL ENERGY COST SAVINGS

Let us look at it. The RMS value of a current pulse train is defined as the value of the DC current, which produces the same amount of losses as the current pulse train. Suppose we have a current pulse train as shown in Fig. 1 which is similar to the main ring pulse.

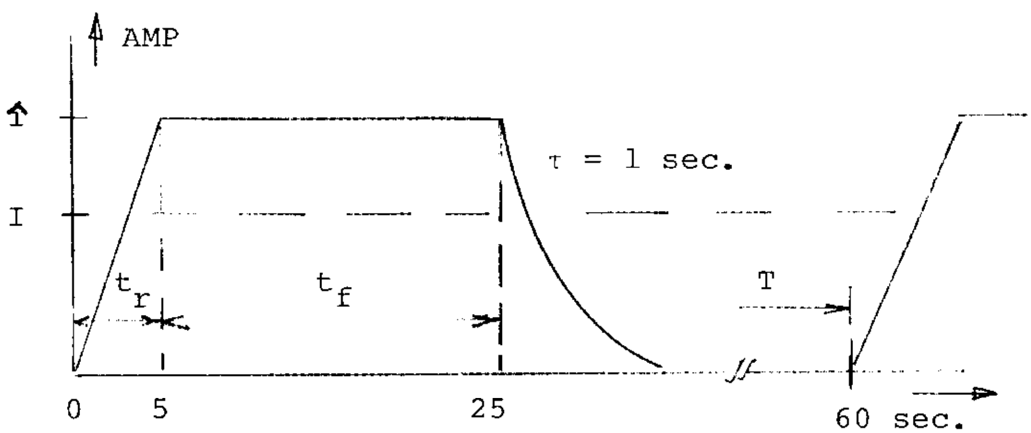


FIG. 1

$\hat{I}$ = Peak current (flattop)
I = RMS current

For this pulse train we can write:

$$I = \hat{I}\sqrt{\frac{1}{T}\left(\frac{t_r}{3} + t_f + \frac{\tau}{2}\right)}$$

$$I = 0.6\,\hat{I}$$

The load losses for this pulse train are:

$$I^2 R_{Load}$$

or: $$0.36\,\hat{I}^2 R_{Load}$$

The DC operating losses would have been $\hat{I}^2\ R_{Load}$. Pulsed operation in synchronism with the main ring pulse produces therefore about 64% less heat losses than DC operation.

Preliminary ramp test results at a modified BM109 show that the magnet field lags the excitation current. The magnet field comes very close to the set field value within 5 seconds after the current reaches flattop. It is therefore reasonable to program the magnet current up 5 seconds ahead of the main ring pulse. This essentially increases the flattop time t_f to 25 sec. and yields:

$$I = 0.67\,\hat{I} \qquad \text{with}$$

$$0.45\,\hat{I}^2\ R_{Load}\ \text{losses.}$$

A typical BM109 operating in an experimenal area might run at 3000A, 80 VDC. This produces 240 KW DC losses or 108 KW ramp losses with a flattop time of 25 sec. and a pulse period of 60 sec. The reduction in losses, when ramping the BM109 magnet as compared to DC operations, is 132 KW. Estimating an energy cost of $0.05 per KWHR we save $6.6 per hr. or a maximum of $58,000 per year. This is a substanial amount of savings, even if a BM109 is only on for 30% of the time. There are probably 10 to 20 magnets that could be commisioned for ramping.

2.1.2 REDUCTION OF LOSSES TO THE COOLING WATER SYSTEM

Magnet heat losses are carried away by the LCW cooling water plant. Any reduction in heat losses is very useful, especially in areas where the cooling plant is operated near its limits. Every 10 KW of heat losses requires about 1 GPM of cooling water flow.

2.1.3 PERMITS HIGHER MAGNET OPERATING CURRENTS

Several BM109's are modified for increased apertures. This results in a reduced magnet field, when the magnet is operated at the same ampere-turns excitation. The magnet steel is in these cases not close to saturation, and the excitation could be increased to produce a proportional increase in magnet field. Cooling water flow can however often not be increased sufficiently to operate the magnet coils beyond their cooling design rating and overtemperature trips will occur. Ramping the magnet allows much higher flattop excitation currents as long as the design limits of the power supply and magnet are not exceeded.

2.1.4 RELEASED AC SUPPLY CAPACITY

All magnet operating losses are supplied from the master substation via AC feeders, local substations and DC power supplies. Any reduction in DC losses puts less load demand at the feeders and the local AC distribution systems.

Experimental areas are constantly changing. Additions of BM109's could require operating an existing AC distribution system beyond its installed AC capacity when DC operation is used. Pulsed operation might therefore be an economical alternative compared to an additional substation, which could cost about $100,000 for 1500 KVA installed. Operating a local substation up to a maximum of 150% of its rated value, during flattop, has been successfully done, as long as the substation RMS current rating is not exceeded.

2.2 DISADVANTAGES

2.2.1 UNKNOWN EFFECTS

We do not know the transient behavior of the magnet and the field and therefore have to study that. Many users might be apprehensive to ramp BM109's, etc. because we have not done it in the past.

2.2.2 REPETITIVE ELECTROMECHANICAL FORCES

The coils in ramped magnets are subject to very large (order of 10,000 KG/m) pulsating electromechanical forces. Coils need therefore to be of a solid potted or cured B-stage tape construction, and solidly supported in the magnet steel so that they cannot move up or down or axially. BM109's have very solid potted coils, which are easily secured. Unpotted or uncured coils, such as those insulated with tape, are generally spongy and should definitely not be ramped.

2.2.3 PULSATING MAGNETIC FIELD

Analyzing magnets have usually large apertures from which a large stray field bulges out. Equipment mounted in this stray field might not be able to withstand repetitive pulsating forces, however some attention to this could overcome this problem in most cases.

Experimental equipment mounted in the magnet aperture might malfunction, due to repetitive magnetic field pulsing. This equipment must always be able to handle trips and startups.

2.2.4 ADDITIONAL COST FOR CONTROLS

All power supplies are remotely programmed through the existing control system.

D.C. operated power supplies run usually via a DC type (#159) control card and ramped supplies from a programmable type (#150) control cards.

A simple exchange of control cards is all that is needed, however, #150 cards are in short supply and new ones cost about $600 each.

2.2.5 MORE DIFFICULT FIELD MONITORING

Several users monitor magnet fields with gaussmeters and or NMR's. Changing field values make monitoring more difficult. Fermilab built NMR's require about 10 seconds to latch onto the magnet field value.

2. PRELIMINARY RAMP TESTS

The BM109, analyzing magnet MP9AN,(Reference 1) installed in the meson polarized experimental hall for Experiment#581/704, is the only analyzing magnet, so far, which has been operated in a ramped mode, for a few months. This magnet has the aperture increased from 8" to 12", which reduces the gap magnetic field per ampere turn excitation.

Running the magnet excitation coils at DC levels beyond their RMS current rating resulted in repetitive overtemperature trips, and it was therefore not possible to reliably attain the required magnetic field. Ramping the magnet was a logical thing to do.

Some quick measurements to check the lag between the excitation curent and the magnet field were made. The results are shown in Fig. 2.

More extensive tests need to be made. There were only a few hours available for testing. It appears that we need to improve our measuring setup and equipment for better accuracy and elimination of common mode noise. The distance between the power supply (DC current transductor) and the magnet is several hundred feet. They are located in different buildings. This made the measurement more cumbersome. Nevertheless, the results shown in Fig. 2 are a very good indication of the lag between the current and the field. Using different power supply regulator tunes affects the lag.

The measuring setup used a nulling scheme (shown in Fig. 3) for sensitive field lag measurements. Fig. 3 shows that the power supply current (transductor output voltage) is balanced to zero against a gaussmeter output voltage. Generally, the transductor output voltage changes linearly with the magnet current and the gaussmeter output voltage linearly with the magnet field.

Once this setup is balanced to zero, it should stay zero if the magnet field and current track perfectly and the instrumentation is linear. The differences that occur during ramping are shown on the bottom trace of Fig. 2. The bottom traces indicate that there are offsets between zero magnet current vs. field balance and flattop magnet current vs. field balance. The input to the recorder should be zero in both cases. It is best to balance this setup during DC operation at the desired flattop current.

The measurements show further that the magnet field slopes up like an e-function during flattop, but tracks the current within 0.3% of the desired field within 5 seconds after the current reaches flattop.

Let us think about that.

For idealized magnet charging with a constant voltage power supply we can write:

$$i = \hat{\hat{i}}\,(1 - e^{-\frac{t}{\tau}})$$

$$i = 0.993\,\hat{\hat{i}}$$

$$i = 0.993 \times 1.25\,\hat{i}$$

i = instantaneous current

$\hat{\hat{i}}$ = peak current at 100% power supply voltage

$\hat{i}$ = desired flattop current

t = 5 sec

τ = 1 sec

100% power supply voltage is 1.25 times the DC flattop voltage.

The value $\hat{\hat{I}}$, where the power supply regulator initially aims for, is higher than the programmed flattop current $\hat{I}$, because the current regulated power supply goes initially full on. This margin is often in the order of 25%. Thus we should be able to reach the required flattop current $\hat{I}$ rather fast (1.6 sec) There is mostly no problem for the curent to reach the flattop value in time.

Real magnets are not ideal and whether the field can track the current depends on the magnet construction. This is because the large blocks of solid iron, from which these magnets are constructed, can support substantial eddy currents, which oppose field changes. Magnet time constants change as a function of the excitation current, frequency and temperature.

The power supply regulator throttles back when the current is close to set value.

What we really want to find out is whether we can program the magnet field in DC type magnets, using the excitation current, while we cannot control the changing transient relation between field and current for different current programs and magnets. We do know however that after a while things settle down during DC operation.

A magnet can be represented by an ideal inductor in series with a resistor, which are in parallel with another resistor and capacitor. See fig. 4 below:

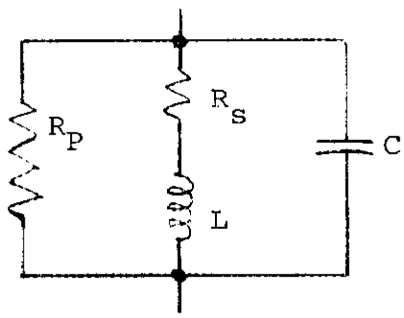


Fig. 4

L represents the magnet inductance, which decreases as the magnet steel saturates.

R_s represents the resistance of the excitation winding which increases about 15% from cold to hot.

C represents stray capacitance and is negligable at the low operating frequencies of less than 1 Hz.

R_p represents the iron losses and depends strongly on the operating frequency, magnet construction and field strength.

$$R_p = \frac{K_1}{f} + \frac{K_2}{f^2}$$

K_1, K_2 are constants determined by the amount of magnet steel, construction, lamination thickness and field strength.

For DC operation f=0 and $R_p = \infty$ For high frequency operation $R_p = 0$ and we will not be able to build up a high frequency magnet field.

DC type magnets are not thinly laminated and R_p becomes small at very low frequencies (in the order of 1 Hz), while the laminated AC type magnets, built for pulsing, have an R_p which is much higher at low frequencies.

The magnets we are looking at are built for DC, but the operating frequency is also very low. The used rate of current rise would compare to a frequency in the order of 0.1 Hz, and we can allow several seconds for the field to settle. It may, under these conditions, be feasible and economical to pulse DC magnets.

From the test results in Fig. 2 we can conclude that 5 seconds is a reasonable settling time. Programming the magnet current 5 seconds ahead of main ring flattop yields a magnet field that does not change more than about +0.3% during main ring flattop (beam spill). This might not be acceptable for some experiments.

However, I think that the flatness of the field, during main ring flattop, could be improved by programming the BM109 current a few percent too high during the 5 second lead period.

These measurements should be repeated, with a better setup, to make sure that this field change is really true and that we are not misled by measuring errors.

Extra coil bracing was installed at the BM109. There was no observable coil motion. It was hard to detect the 3000A excitation pulse while touching the coil. I do not expect any mechanical problems with ramping BM109's.

A.T.V.

FERMILAB ENGINEERING NOTE

SECTION	PROJECT	SERIAL-CATEGORY	PAGE
EED/PSC	VISSER/ ZASKIEWY	OCT 87	

RAMP TESTS AT A MODIFIED BM109 WITH 12" APERTURE. STANDARD AP. IS 8"

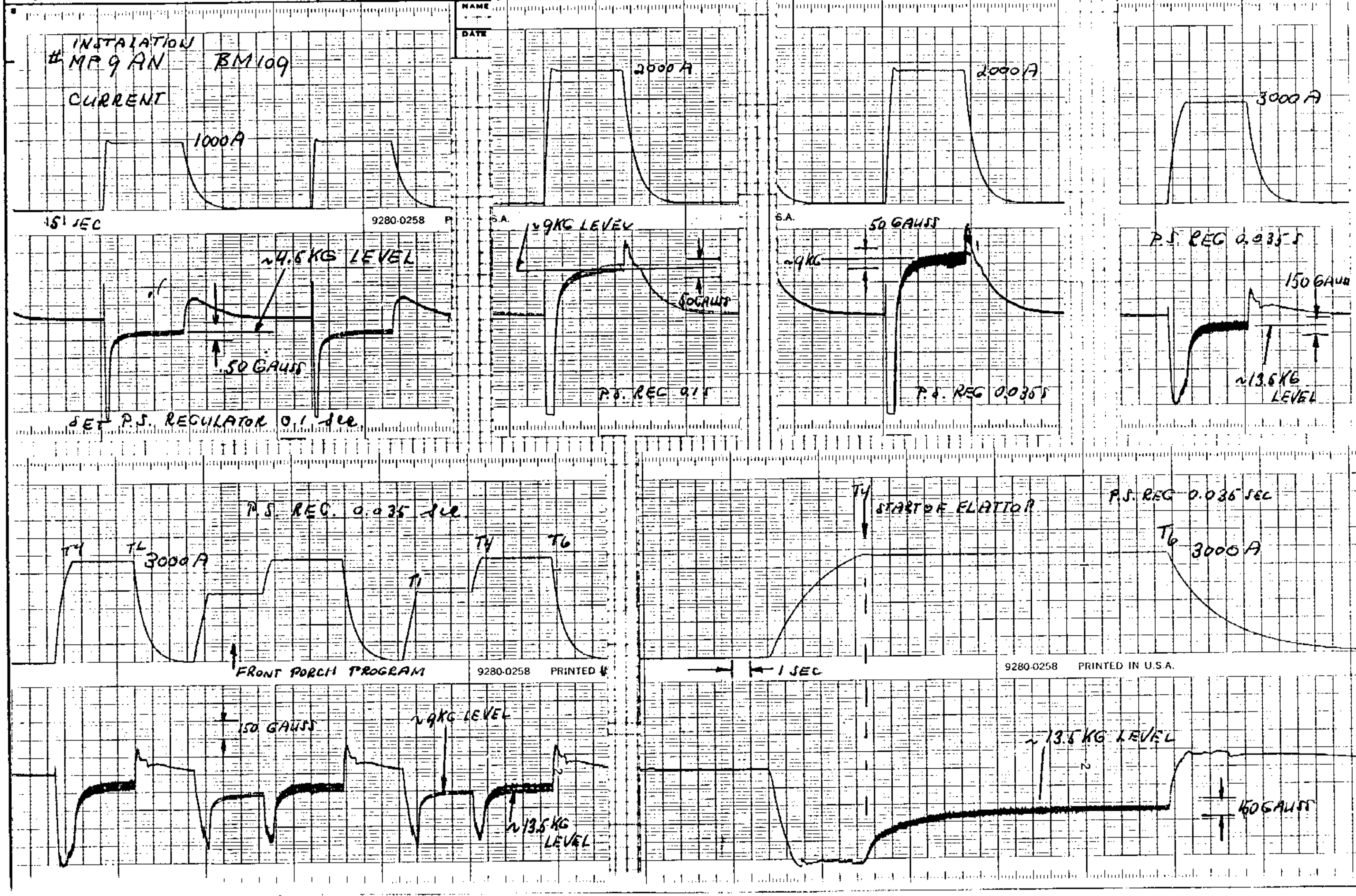


FIG2

FERMILAB
ENGINEERING NOTE

SECTION	PROJECT	SERIAL-CATEGORY	PAGE
EED/PSI	RAMP TEST	MP9AN	

SUBJECT	NAME	DATE	REVISION DATE
FIELD LAG TEST SET UP	A.T. VISSER	OCT 87	

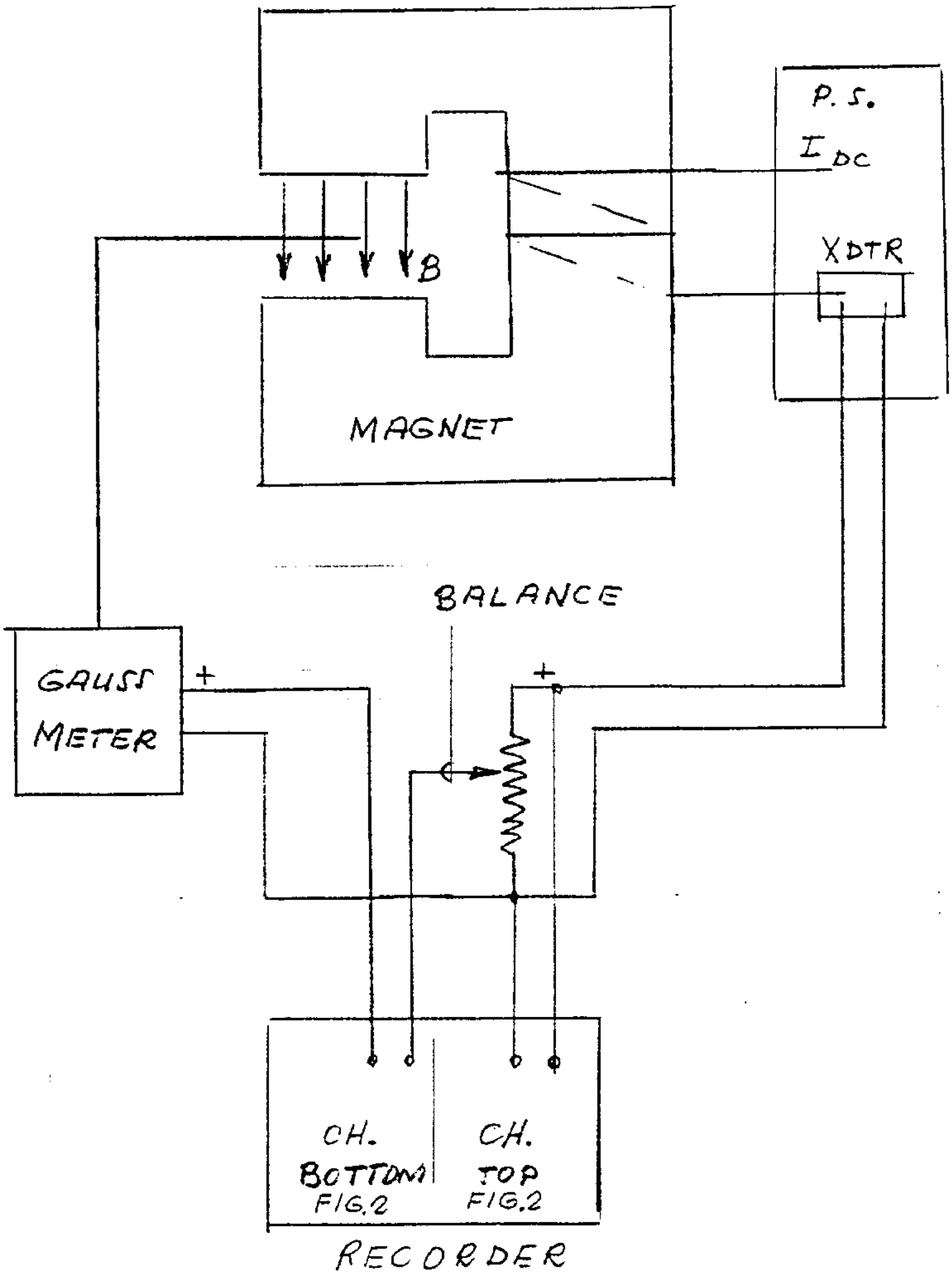


FIG. 3

Modified BM 104

E-57

...INEERING

Magnets

SUBJECT 24/8/72 BENDING MAGNE...

VISSER DATA SHEET

NAME R. McCRACKEN

DATE 10/21/71 REVISION DATE

Magnetic Field: (Design)

Central Field 18.0 KG

Power

D.C. Power 200 KW
Current (Theor.) 2750 A
Voltage (Theor.) 73.0 V
Copper Temp.+ Avg.* 54.4 C
Resistance 26.6 MΩ
2 Coils at ~55°C

73 ÷ 2750 = 26.5 × 10⁻³

total Estimate 32 × 10⁻³ Ω

26.5 × 10⁻³ Ω
27.1 × 10⁻³ Ω @ 60°

Cooling

Water Temp. In. 35° C
Water ΔT 39° C
Flow Req'd 20 gpm
(Throttled)
ΔP Req'd 70 psi

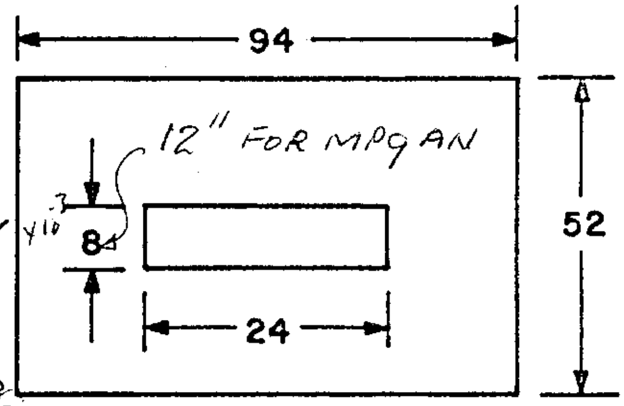
Coil Data

Conductor O.D. 0.914 x 0.886
Hole Dia. 0.360
Turns 112
Water Paths 8

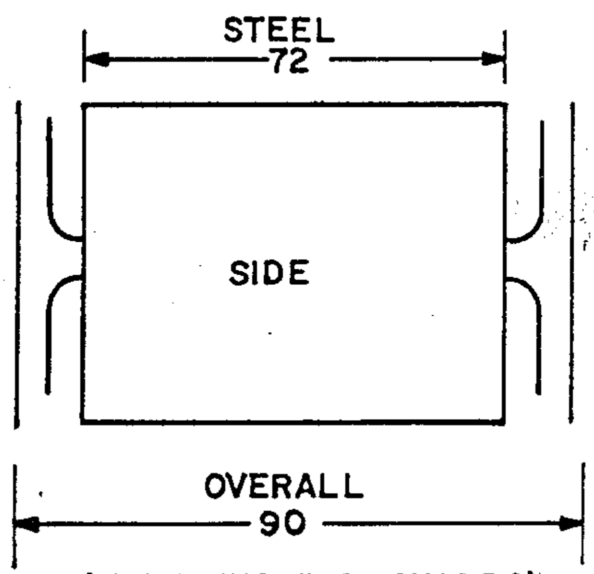
Weights

Core Wt. 90,000 #
2 Coil Wt. 6,600 #
Trailer 8,500 #

+ Calculated from *



CROSS-SECTION



(INCLUDING END GUARDS)

3/5 × 900
550 A

3 KA – 19.62 KG 8" Gap
2806 A – 18.63 KG "

info P. Koehler
BM109
8" Gap

I	½ ∫B dl	B_0
900	214.8	5.794 KG
1500	356.9	9.625
2098	495.9	13.40
2700	626	17.05
3000	679.8	18.63

REFERENCE 1
MODIFIED BM109

ATV.

Fermi National Accelerator Laboratory

TM-1509-A

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BM109 Preliminary Results

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ADDENDUM 1
February 22, 1988

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9204.000

A.T. Visser
1/15/88

RAMPING OF SOLID IRON ANALYSIS MAGNETS IN EXPERIMENTAL AREAS

BM109 PRELIMINARY RESULTS

ADDENDUM 1 (2/22/88)

1. SUMMARY

This addendum lists all D.C. type loads in the experimental areas and concludes that a saving in the order of $1,000,000 per year is feasible by ramping a large portion of these D.C. operated loads.

These savings are based on using the new future main ring pulse with a flattop of 30 seconds and a pulse period of 63 seconds at 800 GeV. This mode of operation was successfully tested in all experimental areas on 2/15/88. It is estimated that the total D.C. magnet load in all experimental areas is about 12.7 MW of which 7.7 MW can be ramped. A conservative ramping program, with a risetime of about 13 seconds, which reaches flattop value 7 seconds ahead of the main ring flattop, appears to be the most practical, but some loads may need overshoot programming. Ramping the presently D.C. operated power supplies requires the installation and procurement of about 40 ramp cards (#150) at a total estimated cost of $24,000. This is a very modest expense compared to the potential savings.

MESON, DC OPERATED MAGENTS

	MAGNET NAME	MAGNET TYPE	OPERATE AT A/V	DC-KW	COMMENTS
1.	MP6D2	EARTLY TGT	1650A/80V	132	SHARE MC6D
2.	MC6D	EARTLY TGT	1600A/77V	123	
3.	MW6W	EARTLY TGT	1313A/94V	123	
4.	ME6AN	BM105	2000A/88V	166	REMOVE IN '88?
5.	ME7AN1	SM12	4000A/290V	1160	SUITABLE?
6.	ME7AN2	JAPAN	4000A/130V	520	SUITABLE?
7.	MC8AN1	BM109	2000A/65V	130	SUITABLE?
8.	MC8AN2/3	CRONIN	1600A/280V	448	SUITABLE?, 2 P.S.
9.	MC8AN4	100D40	2000A/275V	550	
10.	MP7D	BM105	806A/219V	177	
11.	MP7U1	BM105	806A/219V	177	
12.	MP7U2	BM105	1015A/185V	188	
13.	MP9SR1	SNAKE	1010A/224V	226	
14.	MP9SR2	SNAKE	1010A/224V	226	
15.	MP9SR3	SNAKE	1010A/224V	226	
16.	MP9AN	BM109	2700A/98V	265	RAMPING IN USE NOW
17.	MW7S	SPOILERS	350A/80V	28	
18.	MW9AN	36-50-66	2500A/180V	450	
19.	MW9T	TOROID	1800A/36V	65	

A.	TOTAL DC LOAD	5380KW
B.	TOTAL DC LOAD MOST LIKELY SUITABLE FOR RAMPING (DOES NOT INCLUDE ALL?)	2956KW
C.	POWER SAVINGS ITEM B, PROGRAM 1, 34%	1005KW
D.	COST SAVINGS PER 24 HRS AT $0.05 PER KWHR,ITEM C	$1206

NEUTRINO, DC OPERATED MAGNETS

	MAGNET NAME	MAGNET TYPE	OPERATE AT A/V	DC-KW	COMMENTS
1.	NE8U	EARTLY TGT	1200A/35V	42	
2.	NEEAN1	BM109	2500A/160V	400	REMOVE '88?
3.	NEEAN2	40D48	4500A/180V	810	REMOVE '88?
4.	NEHAN	SC104	2400A/320V	768	DO NOT RAMP
5.	NEHT	TOROID	1000A/72V	72	
6.	NCFT	TOROID	1250A/112V	140	
7.	NCHT1	TOROID	750A/112V	84	
8.	NCHT2	TOROID	725A/252V	183	
9.	NM2E2	EARTLY TGT	1313A/59V	77	
10.	NMOT	TOROID	800A/133V	106	RAMPING IN USE
11.	NMSS	SPOILER	100A/20V	2	

A.	TOTAL DC LOAD	2684 KW
B.	TOTAL DC LOAD MOST LIKELY SUITABLE FOR RAMPING	1916 KW
C.	POWER SAVING ITEM B, PROGRAM 1, 34%	651 KW
D.	COST SAVINGS PER 24 HRS AT \$0.05 PER KWHR ITEM C	\$782

PROTON, D.C. OPERATED MAGNETS

	MAGNET NAME	MAGNET TYPE	OPERATE A/V	AT DC-KW	COMMENTS
1.	PC2H	3D120	100A/100V	10	
2.	PC3AN	TARGET	1800A/100V	-	2 OPERATING MODES
			3000A/166V	498	
3.	PC4AN1	BM109	2500A/130V	325	
4.	PC4AN2	BM109	2750A/73V	201	
5.	PB6SW	SWEEP	1700A/73V	124	
6.	PB6CD	3D120	125A/250V	31	
7.	PB6AN1	50-30-66	2500A/160V	400	
8.	PB6AN2	50-30-66	1300A/80V	104	
9.	PB6AN3	SCM105	500A/48V	24	
10.	PB6AN4	(E774)	960A/160V	154	
11.	PE5TAG	TAGGING	830A/323V	268	
12.	PE6AN1	32-72-40	2450A/90V	221	NOT SUITABLE FOR RAMPING
13.	PE6AN2	32-72-40	2450/180V	442	NOT SUITABLE FOR RAMPING
14.	PW7V2	3D120	100A/100V	10	
15.	PW6S1	SPOILER	10A/120V	1	
16.	PW7S1	SPOILER	25A/430V	11	
17.	PW6S2	SPOILER	25A/200V	5	
18.	PW7S2	SPOILER	25A/350V	9	
19.	PW8T	TOROID	1600A/130V	208	
20.	PW8AN1	MASS SEL.	2500A/250V	625	NOT SUITABLE FOR RAMPING
21.	PW8H2	3D120	100A/100V	10	
22.	PW8AN2	ROSIE	2500A/384V	960	NOT SUITABLE FOR RAMPING

A.	TOTAL DC LOAD	4641 KW
B.	TOTAL DC LOAD MOST LIKELY SUITABLE FOR RAMPING	2835 KW
C.	POWER SAVING ITEM B, PROGRAM 1, 34%	964 KW
D.	COST SAVINGS PER 24 HRS AT $0.05 PER KWHR ITEM C	$1157

SUMMARY D.C. OPERATED MAGNET LOADS
EXP. AREAS, PROTON, MESON, NEUTRINO

A.	TOTAL DC LOAD	12,705 KW
B.	TOTAL DC LOAD MOST LIKELY SUITABLE FOR RAMPING	7,707 KW
C.	POWER SAVINGS ITEM B, PROGRAM 1, 34%	2,620 KW
D.	COST SAVINGS PER 24 HRS AT $0.05 PER KWHR ITEM C	$3,144
E.	MAXIMUM ANNUAL SAVINGS ITEM D, 318 DAYS	$1,000,000

2. LISTING OF DC LOADS

Pages 2, 3 and 4 list all the conventional D.C. loads and their operating losses in the experimental areas. The superconducting loads are not included because their long current decay time constants (~70 seconds) do not allow substantial energy savings. Some loads are estimated to be unsuitable for ramping, because of weak coil construction or other expected problems. However, Proton magnets PE6AN1, PE6AN2, and PW8AN2 could be ramped after they are rebuilt. It should also be understood that not all D.C. magnets are fully on at the same time, but the savings are still substantial at a lower total D.C. load.

3. POWER SAVINGS

The power savings of various programs are listed in Fig. 1. The conservative ramping program #1, Fig. 1, yields a 34% power savings and reaches flattop 7 seconds ahead of T5. Theoretical maximum savings of 49% are possible with program #4, but this program will have an unacceptable field lag.

Page 5 summarizes the total savings at 100% D.C. load. It may not be possible to ramp all suitable loads in the Summary due to unacceptable field lag.

4. ADDITIONAL RAMP TESTS

Additional ramp tests were performed at BM109, #MP9AN, which has a 12" gap; BM109, #PC4AN1, which has a 10" gap, and BM109, #PC4AN2 which has a 12" gap. The PC4 magnets have different type coils. Various programs were tried to improve the magnet field lag. Programming the current a few percent higher than the required flattop value, ahead of T5 (start of main ring flattop), improved the field during flattop for PC4AN1 (see Fig. 6). This type of overshoot programming can get rather confusing especially when pulse marker times T2, T3, T4 change. A very simple program, #1, that reaches flattop 7 seconds ahead of T5 is preferred.

Some experimenting with different regulator time constants was done. It appears that the field in both 12" gap BM109's can be made flat to within 0.1% with a program that reaches flattop 7 seconds ahead of T5. Overshoot programming can be made to yield a 0.1% flat field for the 10" BM109. The results of various tests are shown in Figs. 2 through 6. Other different magnets, spoilers and toroids should be tested for field lag, starting out with program #1 of Fig. 1.

The field lag will be different for different magnets and is expected in increase as the gap gets smaller. The field in toroids and spoilers will show the most lag, but these fields are usually not that critical. An understanding of acceptable levels of field lag is essential because the potential savings are substantial. We might conclude that it is not advisable to ramp certain loads, but I am sure that many of them could be easily ramped.

5. SUGGESTED RAMP PROGRAM FOR D.C. LOADS

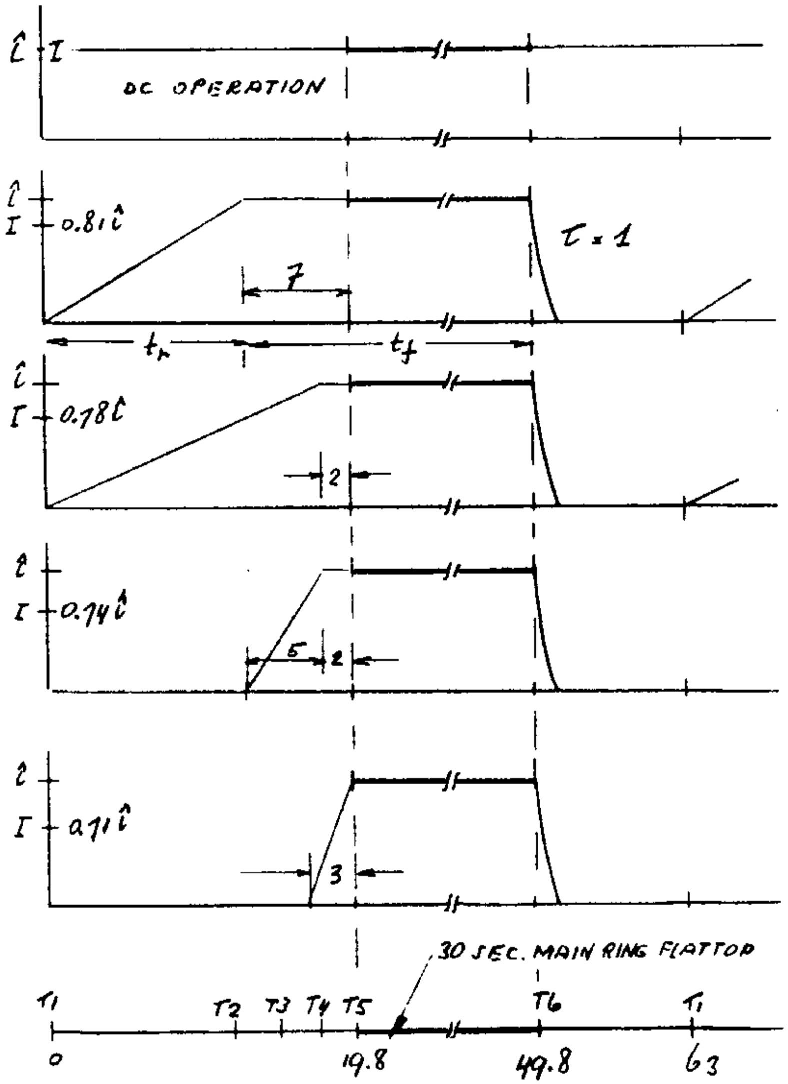
A simple program should be used, even at the expense of a few percent less power savings. Experimenters will abandon troublesome programs that give erratic results. It is therefore suggested to start all ramps for suitable D.C. type loads at T1 with a slope $\hat{I}/13$ that reaches flattop 7 seconds ahead of T5. This type of program (Fig. 1, #1) yields 34% power savings and is gentle on the equipment due to the slow rate of current rise. Field lag tests will indicate whether small program modifications are required or whether programming should be abandoned for a particular load.

6. A WORD OF THANKS

I would like to thank Walt Jaskierny and Julius Lentz for their valuable suggestions about the many ramp tests they successfully performed.

A.T.V.

FERMILAB ENGINEERING NOTE	SECTION	PROJECT	SERIAL-CATEGORY	PAGE
	PSI	TM1509	ADD. #1	FIG 1
SUBJECT: POWER SAVINGS FOR DIFFERENT PULSE PROGRAMS	NAME: A.T. VISSER			
	DATE	REVISION DATE		



PROGRAM	POWER SAVINGS COMPARED TO D.C. OPERATION	BM109 # MPq AN COMMENTS
0	0%	P.S. REGULATION 0.05% $\hat{\imath} = I$ 2750A THERMAL LIMIT
1	34%	$\hat{\imath} = 3200A$ $B \sim 14.5$ KG FIELD IS 0.035% LOW AT T5 t_r SLOPE 250 A/SEC
2	39%	$\hat{\imath} = 3200A$ $B \sim 14.5$ KG FIELD IS 0.3% LOW AT T5 t_r SLOPE ~ 180 A/SEC
3	44%	$\hat{\imath} = 3200A$ $B \sim 14.5$ KG FIELD IS ~ 5% LOW AT T5 NOT ACCEPTABLE
4	49% MAXIMUM POSSIBLE SAVINGS	$\hat{\imath} = 3200A$ $B \sim 14.5$ KG FIELD IS > 5% LOW AT T5 POWER SUPPLY VOLTAGE LIMIT

TIME SEC

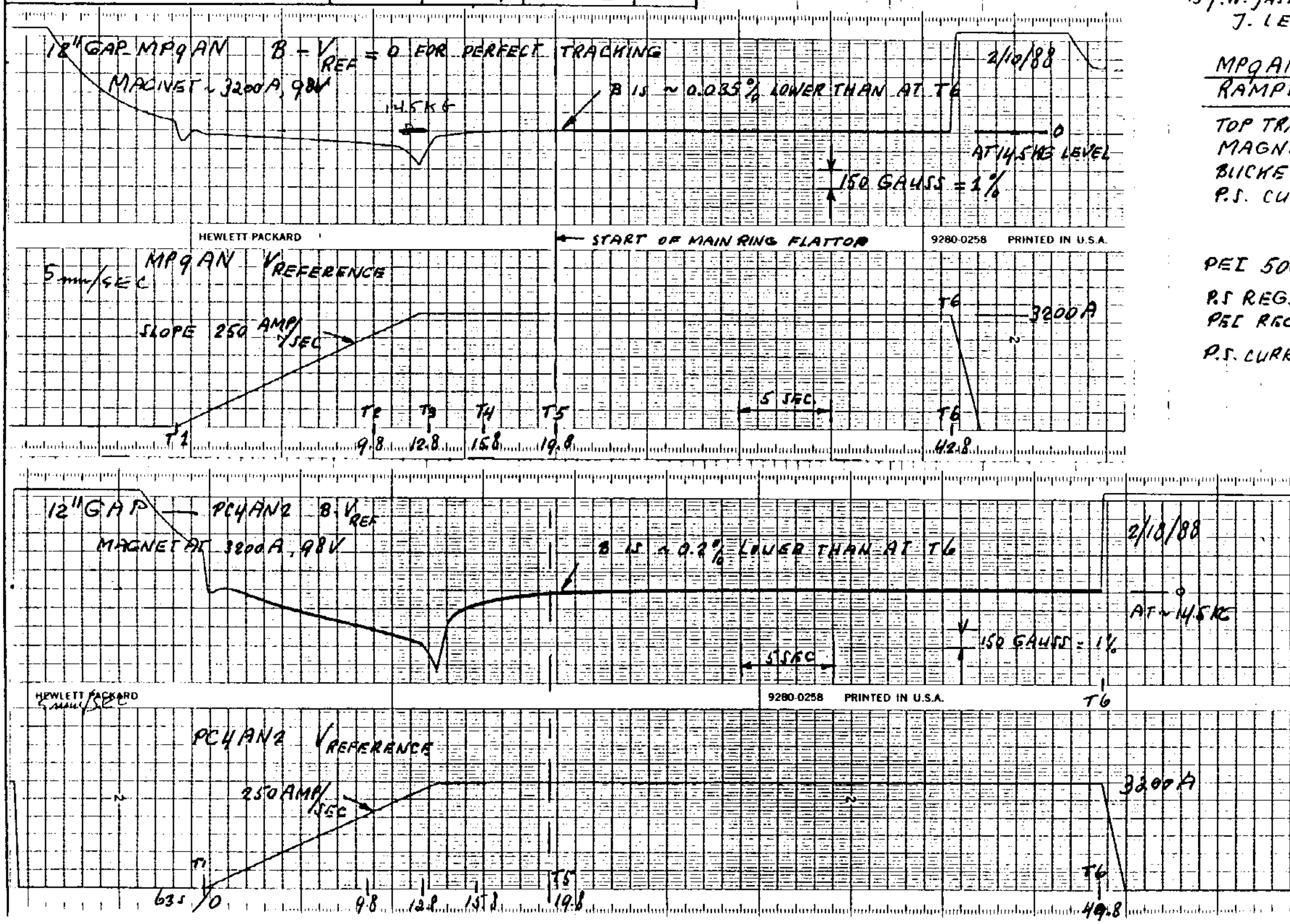
$$I = \hat{\imath}\sqrt{\frac{1}{63}\left(\frac{t_r}{3} + t_f + \frac{\tau}{2}\right)} \quad \text{AMP.}$$

$$\text{POWER SAVING} = \frac{\hat{\imath}^2 - I^2}{\hat{\imath}^2}\,100\%$$

FIG 1

FERMILAB ENGINEERING NOTE	SECTION	PROJECT	SERIAL-CATEGORY	PAGE	
	PSI	TM1509	ADD. #1	FIG 2	AT. VISSER

By: W. JASKIERNY
J. LENZ



MP9AN, BM109
RAMPTEST, 2/10/88

TOP TRACE SHOWS MAGNET FIELD B BUCKED AGAINST P.S. CURRENT REF.

PEI 500KW P.S.

P.S. REG. TIME CONS. 20×10^{-3} S
PEI REGULATOR

P.S. CURRENT REF.

PC4AN2, BM109
RAMPTEST, 2/18/88

TRANSREX 500KW P.S.

P.S. REG. TIME CONST. 0.5 SEC.

(TRANSREX REGULATOR AS BUILD)

FIG 2

FERMILAB ENGINEERING NOTE

SECTION	PROJECT	SERIAL-CATEGORY	PAGE	
PSI	TM1509	ADD. #1	FIG3	A.T. VISSER

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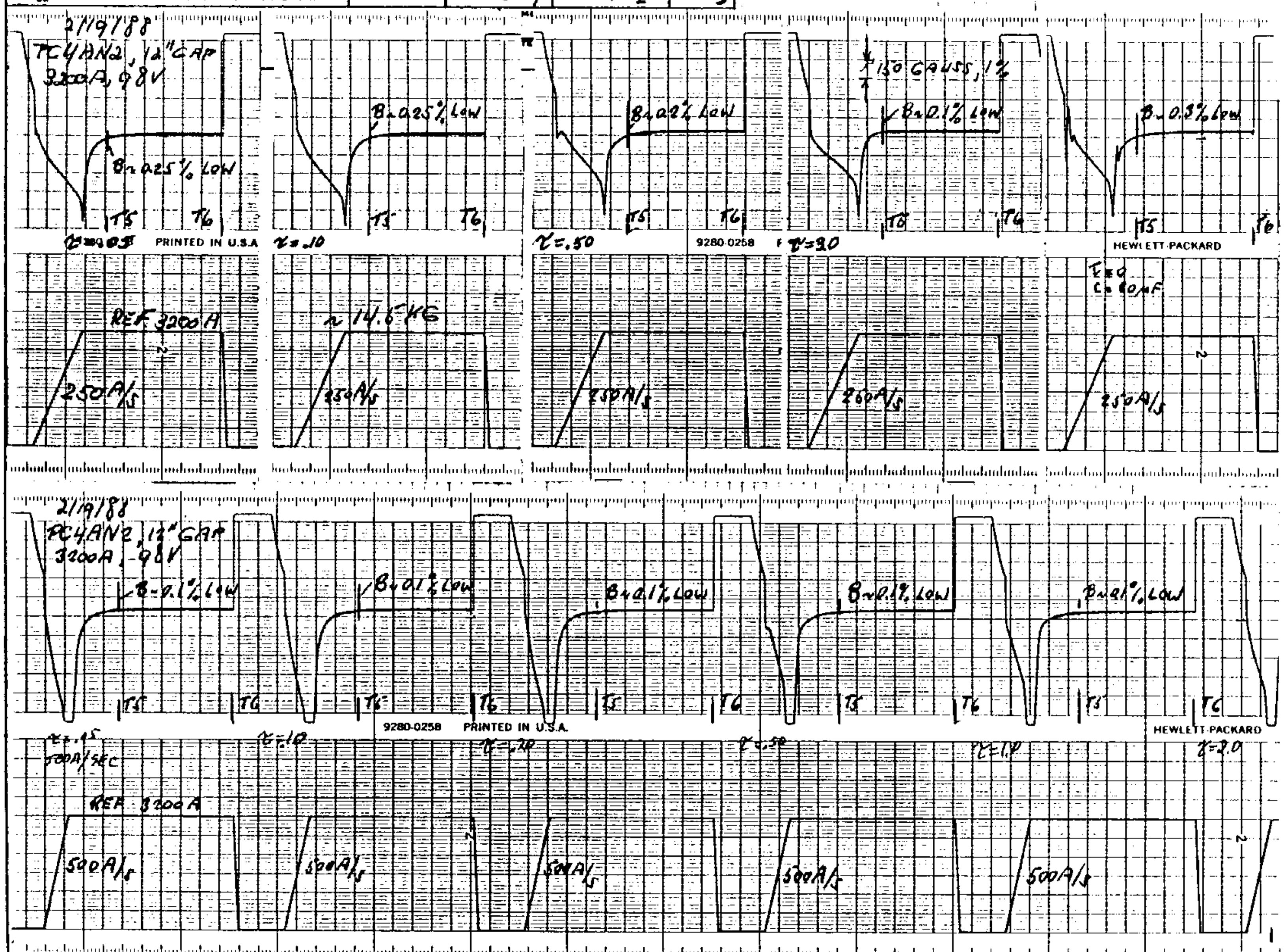

<u>PC4AN2, 8M109</u>
<u>RAMP TEST</u> 2/19/88

TOP TRACE SHOWS
MAGNET FIELD B
BUCKED AGAINST
P.S. CURRENT REF.

P.S. 500KW TRANSREX
AS BUILD P.S. TRANSREX
REGULATOR MODIFIED
FOR DIFFERENT
TIME CONST τ
SETTING

FIG 3
<u>FIELD LAG</u>
<u>FOR DIFFERENT</u>
<u>SLOPES AND</u>
<u>AND P.S. REGULATOR</u>
<u>TIME CONSTANTS</u> τ

FERMILAB ENGINEERING NOTE | SECTION: PSI | PROJECT: TM1509 | SERIAL-CATEGORY: ADD. #1 | PAGE: FIG4 | A.T. VISSER

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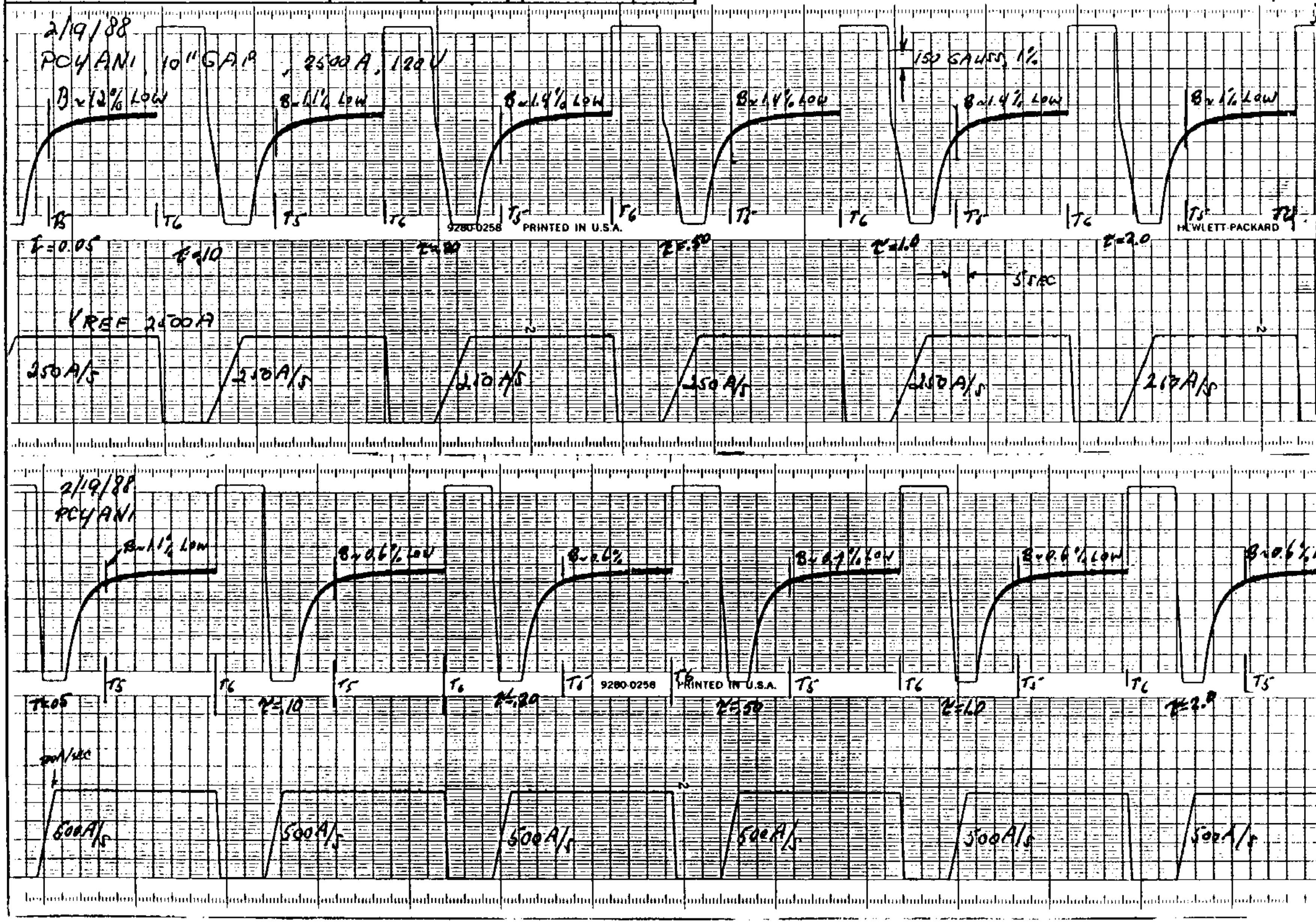
J. LENZ



PCYANI, BM109
RAMP TEST 2/19/88

TOP TRACE
MAGNET B
BUCKED AGAINST
P.S. CURRENT REF

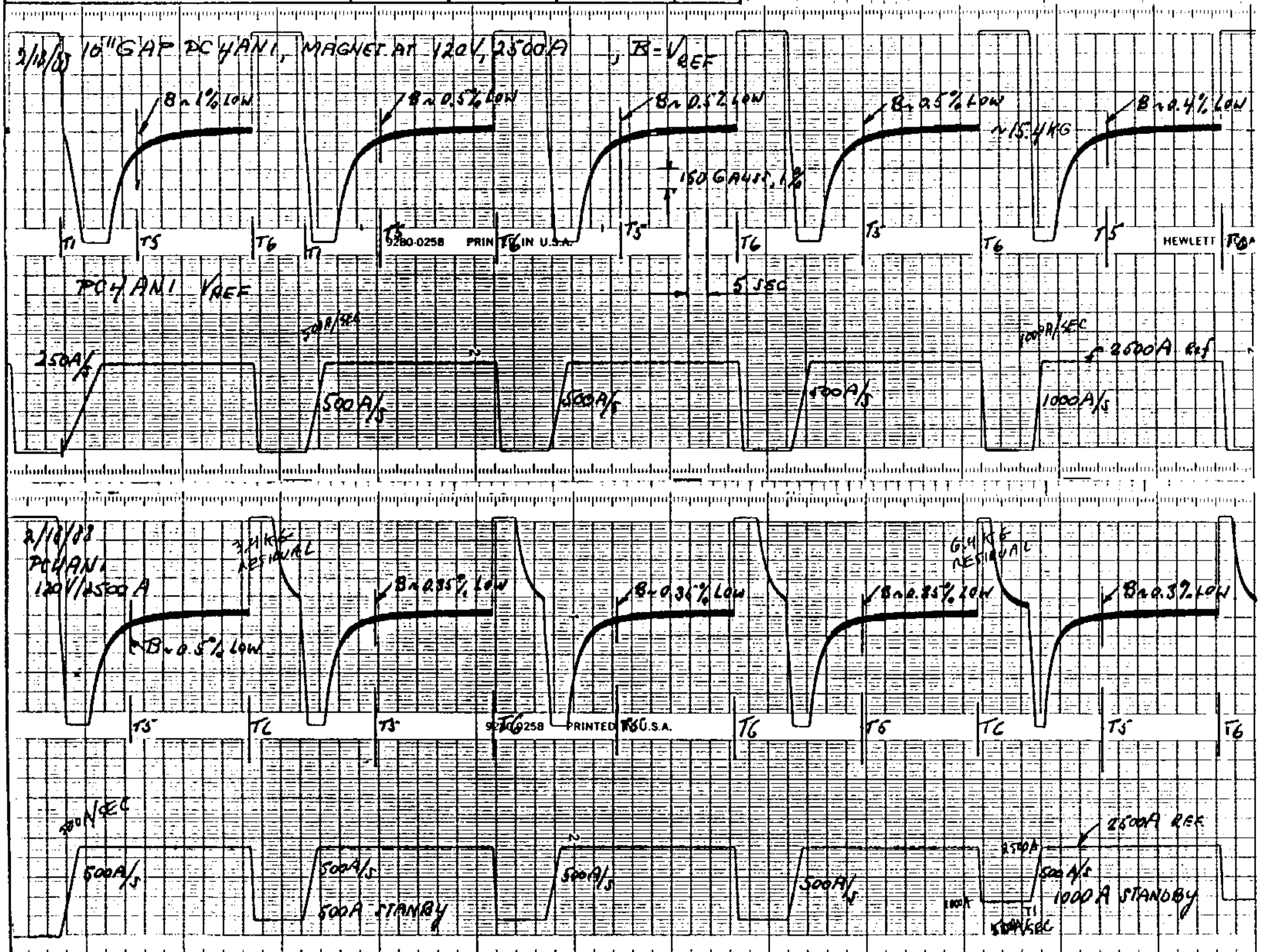
P.S. 500 KW. TR
REG. MODIFIED
FOR DIFFERENT
TIME CONST. τ
SETTINGS

FIG. 4

FIELD LAG
FOR DIFFERENT
SLOPES AND
P.S. REGULATOR TIME
CONSTANTS τ

FERMILAB ENGINEERING NOTE

SECTION	PROJECT	SERIAL-CATEGORY	PAGE	
PSI	TM1509	ADD #1	FIG5	A.T. VISSER



BY: W. JASKIERNY
J. LENZ

PC4ANI, BM109
RAMPTESTS, 2/18/88

TOP TRACE SHOWS MAGNET FIELD B BUCKED AGAINST P.S. CURRENT REF

P.S. 500KW TRANSREX

P.S. REGULATOR TIME CONST. 0.5 SEC

TRANSREX REG AS BUILD

FIG. 5
FIELD LAG WITH VARIOUS SLOPES AND STANDBY LEVELS.

FERMILAB ENGINEERING NOTE	SECTION	PROJECT	SERIAL-CATEGORY	PAGE
	PSI	TM1509	ADD #1	FIG 6

A.T. VISSER

BY WFJ/JL 2/19/88

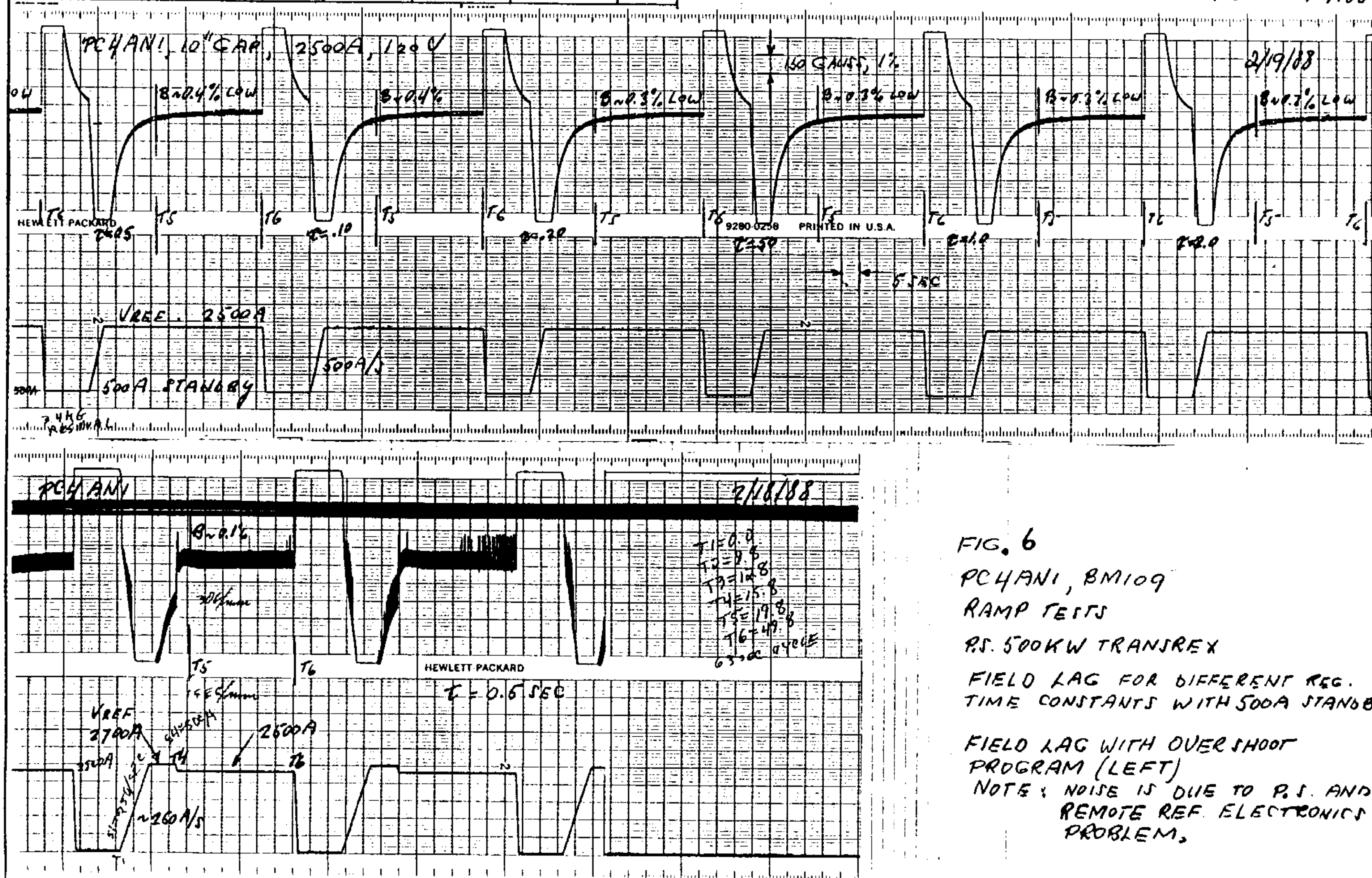


FIG. 6

PC4ANI, BM109

RAMP TESTS

P.S. 500KW TRANSREX

FIELD LAG FOR DIFFERENT REG. TIME CONSTANTS WITH 500A STANDBY (TOP)

FIELD LAG WITH OVERSHOOT PROGRAM (LEFT)

NOTE: NOISE IS DUE TO P.S. AND REMOTE REF. ELECTRONICS PROBLEM.